11 MULTIPLE RADIONUCLIDES

There are two cases to be considered when dealing with multiple radionuclides, namely (1) when the radionuclide concentrations have a fairly constant ratio throughout the survey unit, or (2) when the concentrations of the different radionuclides appear to be unrelated in the survey unit. In statistical terms, we are concerned about whether the concentrations of the different radionuclides are correlated or not. A simple way to judge this would be to make scatter plots of the concentrations against each other, and see if the points appear to have an underlying linear pattern. The correlation coefficient can also be computed to see if it lies nearer to zero than to one. One could also perform a curve fit and test the significance of the result. Ultimately, however, sound judgment must be used in interpreting the results of such calculations. If there is no physical reason for the concentrations to be related, they probably are not. Conversely, if there is sound evidence that the radionuclide concentrations should be related because of how they were treated, processed or released, this information should be used.

11.1 Using the Unity Rule

In either of the two above cases, the unity rule described in Section 3.3 is applied. The difference is in how it is applied. Suppose there are n radionuclides. If the concentration of radionuclide i is denoted by C_i, and its $\mathrm{DCGL_W}$ is denoted by D_i, then the unity rule for the n radionuclides states that

$$C_1/D_1 + C_2/D_2 + C_3/D_3 + \cdots + C_n/D_n \leq 1 \qquad (11\text{-}1)$$

This will ensure that the total dose due to the sum of all the radionuclides does not exceed the release criterion. Note that if D_{min} is the smallest of the DCGLs, then

$$(C_1 + C_2 + C_3 + \cdots + C_n)/D_{\mathrm{min}} \leq C_1/D_1 + C_2/D_2 + C_3/D_3 + \cdots + C_n/D_n \qquad (11\text{-}2)$$

So that the smallest DCGL may be applied to the total activity concentration, rather than using the unity rule. While it is an option to consider, in many cases this approach will be too conservative to be useful.

11.2 Radionuclide Concentrations With Fixed Ratios

If there is an established ratio among the concentrations of the n radionuclides in a survey unit, then the concentration of every radionuclide can be expressed in terms of any one of them, e.g., radionuclide #1. The measured radionuclide is often called a *surrogate* radionuclide for the others.

If $C_2 = R_2C_1$, $C_3 = R_3C_1$, ..., $C_i = R_iC_1$, ..., $C_n = R_nC_1$,
then

$$\begin{aligned} C_1/D_1 + C_2/D_2 + C_3/D_3 + \cdots + C_n/D_n &= C_1/D_1 + R_2C_1/D_2 + R_3C_1/D_3 + \cdots + R_nC_1/D_n \\ &= C_1\,[1/D_1 + R_2/D_2 + R_3/D_3 + \cdots + R_n/D_n\,] \\ &= C_1/D_{\mathrm{total}}\,, \qquad (11\text{-}3) \end{aligned}$$

where

$$D_{total} = 1/\,[1/D_1 + R_2/D_2 + R_3/D_3 + \cdots + R_n/D_n\,]. \tag{11-4}$$

Thus, D_{total} is the $DCGL_W$ for the surrogate radionuclide when the concentration of that radionuclide represents all radionuclides that are present in the survey unit. Clearly, this scheme is applicable only when radionuclide-specific measurements of the surrogate radionuclide are made. It is unlikely to apply in situations where the surrogate radionuclide appears in background, since background variations would tend to obscure the relationships between it and the other radionuclides.

Thus, in the case in which there are constant ratios among radionuclide concentrations, the statistical tests are applied as if only the surrogate radionuclide were contributing to the residual radioactivity, with the $DCGL_W$ for that radionuclide replaced by D_{total}. For example, in planning the final status survey, only the expected standard deviation of the concentration measurements for the surrogate radionuclide is needed to calculate the sample size.

For the elevated measurement comparison, the $DCGL_{EMC}$ for the surrogate radionuclide is replaced by

$$E_{total} = 1/\,[1/E_1 + R_2/E_2 + R_3/E_3 + \cdots + R_n/E_n\,], \tag{11-5}$$

where E_i is the $DCGL_{EMC}$ for radionuclide i.

11.3 Unrelated Radionuclide Concentrations

If the concentrations of the different radionuclides appear to be unrelated in the survey unit, then there is little alternative to measuring the concentration of each radionuclide and using the unity rule. The exception would be in applying the most restrictive $DCGL_W$ to all of the radionuclides, as mentioned in Section 11.1.

Since the release criterion is

$$C_1/D_1 + C_2/D_2 + C_3/D_3 + \cdots + C_n/D_n \le 1.0 \tag{11-6}$$

the quantity to be measured is the *weighted sum*, $T = C_1/D_1 + C_2/D_2 + C_3/D_3 + \cdots + C_n/D_n$. The $DCGL_W$ for T is 1.0. In planning the final status survey, the measurement standard deviation of the weighted sum, T, is estimated by

$$\sigma^2(T) = [\sigma(C_1)/D_1]^2 + [\sigma(C_2)/D_2]^2 + [\sigma(C_3)/D_3]^2 + \cdots + [\sigma(C_n)/D_n]^2, \tag{11-7}$$

since the measured concentrations of the various radionuclides are assumed to be uncorrelated.

For the elevated measurement comparison, the inequality

$$C_1/E_1 + C_2/E_2 + C_3/E_3 + \cdots + C_n/E_n \le 1.0 \tag{11-8}$$

is used, where E_i is the $DCGL_{EMC}$ for radionuclide *i*. For scanning, most restrictive $DCGL_{EMC}$ should generally be used.

When some of the radionuclides also appear in background, the quantity
$T = C_1 / D_1 + C_2 / D_2 + C_3 / D_3 + \cdots + C_n / D_n$
must also be measured in an appropriate reference area. If radionuclide *i* does not appear in background, set $C_i = 0$ in the calculation of T for the reference area.

Note that if there is a fixed ratio between the concentrations of some radionuclides, but not others, a combination of the method of this section with that of the previous section may be used, using the appropriate value of D_{total} with the concentration of the measured surrogate radionuclide to replace the corresponding terms in Equation 11-7.

11.4 Example Application of WRS Test to Multiple Radionuclides

This section contains an example application of the nonparametric statistical methods in this report to sites that have residual radioactivity from more than one radionuclide. Consider a site with both ^{60}Co and ^{137}Cs contamination. ^{137}Cs appears in background from global atmospheric weapons tests at a typical concentration of about 1 pCi/g. Assume that the $DCGL_W$ for ^{60}Co is 2 pCi/g and that for ^{137}Cs is 1.4 pCi/g. In disturbed areas, the background concentration of ^{137}Cs can vary considerably. An estimated spatial standard deviation of 0.5 pCi/g for ^{137}Cs will be assumed. During remediation it was found that the concentrations of the two radionuclides were not well correlated in the survey unit. ^{60}Co concentrations were more variable than the ^{137}Cs concentrations, and 0.7 pCi/g is assumed for its standard deviation. Measurement errors for both ^{60}Co and ^{137}Cs using gamma spectrometry will be small compared to this. For the comparison to the release criteria, the weighted sum of the concentrations of these radionuclides is computed from the following:

Weighted sum = (^{60}Co concentration)/(^{60}Co $DCGL_W$) + (^{137}Cs concentration)/(^{137}Cs $DCGL_W$)

= (^{60}Co concentration)/(2) + (^{137}Cs concentration)/(1.4)

The variance of the weighted sum, assuming that the ^{60}Co and ^{137}Cs concentrations are spatially unrelated is

σ^2 = [(^{60}Co standard deviation)/(^{60}Co $DCGL_W$)]^2 + [(^{137}Cs standard deviation)/(^{137}Cs $DCGL_W$)]^2

$= [(0.7)/(2)]^2 + [(0.5)/(1.4)]^2 = 0.25.$

Thus $\sigma = 0.5$. The $DCGL_W$ for the weighted sum is one. Scenario A will be used, i.e., the null hypothesis is that the survey unit exceeds the release criterion. During the DQO process, the LBGR was set at 0.5 for the weighted sum, so that $\Delta = DCGL_W - LBGR = 1.0 - 0.5 = 0.5$, and $\Delta/\sigma = 0.5/0.5 = 1.0$. The acceptable error rates chosen were $\alpha = \beta = 0.05$. To achieve this, 32 samples each are required in the survey unit and the reference area.

The weighted sums are computed for each measurement location in both the reference area and the survey unit. The WRS test is then performed on the weighted sum. The calculations for this example are shown in Table 11.1.

Table 11.1 Example WRS Test for Two Radionuclides

	Reference Area		Survey Unit		Weighted Sum			Ranks	
	^{137}Cs	^{60}Co	^{137}Cs	^{60}Co	Ref	Survey	Adj Ref	Survey	Adj Ref
1	2	0	1.12	0.06	1.43	0.83	2.43	1	56
2	1.23	0	1.66	1.99	0.88	2.18	1.88	43	21
3	0.99	0	3.02	0.56	0.71	2.44	1.71	57	14
4	1.98	0	2.47	0.26	1.41	1.89	2.41	23	55
5	1.78	0	2.08	0.21	1.27	1.59	2.27	9	50
6	1.93	0	2.96	0.00	1.38	2.11	2.38	37	54
7	1.73	0	2.05	0.20	1.23	1.56	2.23	7	46
8	1.83	0	2.41	0.00	1.30	1.72	2.30	16	52
9	1.27	0	1.74	0.00	0.91	1.24	1.91	2	24
10	0.74	0	2.65	0.16	0.53	1.97	1.53	27	6
11	1.17	0	1.92	0.63	0.83	1.68	1.83	13	18
12	1.51	0	1.91	0.69	1.08	1.71	2.08	15	32
13	2.25	0	3.06	0.13	1.61	2.25	2.61	47	63
14	1.36	0	2.18	0.98	0.97	2.05	1.97	30	28
15	2.05	0	2.08	1.26	1.46	2.12	2.46	39	58
16	1.61	0	2.30	1.16	1.15	2.22	2.15	45	41
17	1.29	0	2.20	0.00	0.92	1.57	1.92	8	25
18	1.55	0	3.11	0.50	1.11	2.47	2.11	59	35
19	1.82	0	2.31	0.00	1.30	1.65	2.30	11	51
20	1.17	0	2.82	0.41	0.84	2.22	1.84	44	19
21	1.76	0	1.81	1.18	1.26	1.88	2.26	22	48
22	2.21	0	2.71	0.17	1.58	2.02	2.58	29	62
23	2.35	0	1.89	0.00	1.68	1.35	2.68	3	64
24	1.51	0	2.12	0.34	1.08	1.68	2.08	12	33
25	0.66	0	2.59	0.14	0.47	1.92	1.47	26	5
26	1.56	0	1.75	0.71	1.12	1.60	2.12	10	38
27	1.93	0	2.35	0.85	1.38	2.10	2.38	34	53
28	2.15	0	2.28	0.87	1.54	2.06	2.54	31	61
29	2.07	0	2.56	0.56	1.48	2.11	2.48	36	60
30	1.77	0	2.50	0.00	1.27	1.78	2.27	17	49
31	1.19	0	1.79	0.30	0.85	1.43	1.85	4	20
32	1.57	0	2.55	0.70	1.12	2.17	2.12	42	40
Avg	1.62	0	2.28	0.47	1.16	1.86	2.16	Sum = 799	Sum = 1281
Std Dev	0.43	0	0.46	0.48	0.31	0.36	0.31		

In Scenario A, the $DCGL_W$ (i.e., 1.0) is added to the weighted sum for each location in the reference area. The ranks of the combined survey unit and adjusted reference area weighted sums are then computed. The sum of the ranks of the adjusted reference area weighted sums is then compared to the critical value for $n = m = 32$, $\alpha = 0.05$, which is 1162 (see formula following

Table A.4). In Table 11.1, the sum of the ranks of the adjusted reference area weighted sums is 1281. This exceeds the critical value, so the null hypothesis is rejected. The survey unit meets the release criterion. The difference between the mean of the weighted sums in the survey unit and the reference area is 1.86 − 1.16 = 0.7. Thus, the estimated dose due to residual radioactivity in the survey unit is 70% of the release criterion.